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## ANALYSIS OF CORUNDUM CERAMICS STRENGTH (A Review)

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Based on 50 compact and porous corundum materials with sintering additives, the dependence of the material strength on the strength of the interparticle contacts  $P$ , the interlayer thickness  $h$ , the particle size  $d$ , and the amount of additive is analyzed. A linear dependence of  $P$  on  $d$  for porous materials and a quadratic dependence of  $P$  on  $d^2$  for compact materials are established. It is shown that the parameter  $P$  is more sensitive to the structural parameters of the material than the material strength.

The development of contemporary materials, including ceramics, calls for clarification of the interrelations between their macroscopic properties and structural specifics, including microscopic parameters of the component phases. This is possible in the case of overcoming the difference in the approaches to describing these systems in the context of macromechanics and physics of the solid body. The problem is rather complicated both with respect to the construction of a correct mathematical model of the material structure, and account of the surface interphase and interparticle interactions [1, 2]. It is known that numerous factors affect the strength of ceramic materials, such as the size of the solid phase crystals; the thickness of the intermediate phase interlayers; the integral porosity value, the size and size distribution of the pores; the state of the surface of the samples; the type of stressed state; and the test methods [3].

At present qualitative and, in some cases, semiquantitative models have been developed, which relate certain integral parameters of the material structure (porosity, packing density, pore and particle sizes) to the strength, elasticity modulus, and thermal conductivity. In particular, the semi-empirical dependence of strength  $\sigma$  on porosity  $\Pi$  and particle size  $d$  of ceramic material,

$$\sigma = kd^{-a} \exp(-b\Pi),$$

is widely used, where  $k$ ,  $a$ , and  $b$  are empirical constants.

The values of the constants depend on the fracture mechanism and the nature and structure of the material [4, 5]. It is generally recognized that  $a$  in the intercrystalline fracture is equal to about 0.25 and in the transcrystalline fracture it is 0.5. However, a clear dependence between the strength and

the microscopic parameters of a structure has not been established even for well-studied materials based on aluminum oxide. The values of the coefficient  $a$  significantly differ for corundum ceramics containing the vitreous phase (BK-94-1, MX-1) and those without the vitreous phase (BK-100, Lukalox).

Since ceramic materials are structurally inhomogeneous, they should be considered as disperse systems with the phase (condensation) nature of contacts, and therefore, the effect of the surface of the component grains, the interphase, and intergranular boundaries can be significant.

The effect of the interparticle (intergranular) boundaries on the properties of metals and alloys has been determined [6]. The role of this factor in the high-temperature deformation of ceramics has been described [4], but the established dependences are qualitative.

Since the strength of a polydisperse material is determined not only by the particle strength but also by the strength of the interparticle (intergranular) contact  $P$  between them, an attempt was made to elucidate the dependence of this value on the size of the particles comprising the material. The data published in Russia [7–11] and abroad [12, 13], as well as research data on dense corundum materials [14, 15], were studied. The properties of dense materials based on aluminum oxide with different additives are shown in Table 1. Furthermore, the strength parameters of granular materials based on corundum abrasive powders made according to OST MT 71-5-84 with a finely disperse zirconium dioxide additive (1) and with an additive of the eutectic composition  $\text{ZrO}_2 - \text{Al}_2\text{O}_3$  (2) were assessed. It should be noted that the interparticle contact in granular materials is understood as a point contact, while in dense materials it is an extended contact along the boundary between two particles. The proper-

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ties of filter materials based on corundum abrasive powders are shown in Table 2.

The analysis was performed using one of the simplest percolation models suggested by E. D. Shchukin [16]. According to this model, the determining value for a monodisperse structure consisting of equidimensional spherical particles with diameter  $d$  is the average number of particles  $n$  located between the lattice points. The value  $n$  depends on the packing density (porosity)

$$\Pi(1 - \Pi)^{-1} = (6n^3 / (3\pi n - 2\pi)) - 1$$

and relates the integral mechanical strength of the material to the interparticle contact strength

$$\sigma = P(1/d^2)(\alpha/n)^2,$$

where  $\alpha$  is a parameter depending on  $n$ ,

$$\alpha^2 = (4/\pi)n - (4/3n) - 2.$$

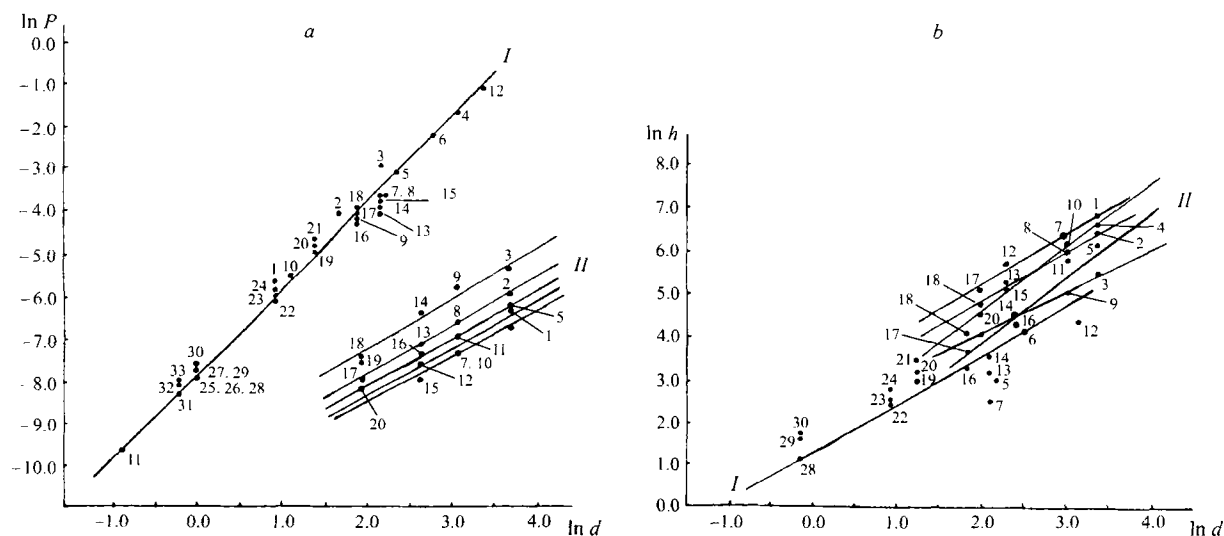
The model is true for materials whose porosity is below 48% [17]. With a porosity below 26%, the number of contacts per 1 cm<sup>3</sup> of material volume is constant; therefore, for dense material we take:

$$P = \sigma d^2.$$

The values of the strength of dense materials in logarithmic coordinates are grouped within a narrow range and do not depend on the crystal size (correlation coefficient less than 0.10). The strength of the porous materials regularly de-

TABLE 1

No.	Material	Additive	Additive weight content, %	Particle size, $\mu\text{m}$	Bending strength, MPa	Reference
1	Sicor	Sc <sub>2</sub> O <sub>3</sub>	1.00	2.5	540 ± 50	[7]
2	The same	The same	1.00	5.0	650 ± 70	[7]
3	The same	The same	1.00	8.0	750 ± 60	[7]
4	The same	The same	1.00	20.0	450 ± 50	[7]
5	Coral-2	Al <sub>2</sub> O <sub>3</sub> - ZrO <sub>2</sub>	1.00	10.0	400	[8]
6	Corundum	Glass	1.00	15.0	440	[9]
7	The same	MgO	0.50	8.0	375	[9]
8	The same	The same	0.50	8.0	235	[9]
9	A-94 T	MgOSiO <sub>2</sub> - TiO <sub>2</sub> - SiO <sub>2</sub>	6.00	6.0	420	[10]
10	GB-7B	SiO <sub>2</sub> - CaO - BaO - B <sub>2</sub> O <sub>3</sub>	3.00	3.0	450	[11]
11	Corundum	CuO - TiO <sub>2</sub> - B <sub>2</sub> O <sub>3</sub> - MgO	2.00	0.4	396	[12]
12	Lucalox	MgO	0.25	30.0	350	[13]
13	Corundum 1	MnO - Al <sub>2</sub> O <sub>3</sub> - SiO <sub>2</sub> , ZrO <sub>2</sub>	2.00	8.0	260 ± 85	[14, 15]
14	The same	The same	3.00	8.0	300 ± 75	[14, 15]
15	The same	The same	4.00	8.0	340 ± 60	[14, 15]
16	Corundum 2	The same	2.00	6.0	400 ± 75	[14, 15]
17	The same	The same	3.00	6.0	440 ± 60	[14, 15]
18	The same	The same	4.00	6.0	500 ± 50	[14, 15]
19	Corundum 3	The same	2.00	4.0	430 ± 50	[14, 15]
20	The same	The same	3.00	4.0	450 ± 50	[14, 15]
21	The same	The same	4.00	4.0	538 ± 45	[14, 15]
22	Corundum 4	The same	2.00	2.5	375 ± 75	[14, 15]
23	The same	The same	3.00	2.5	400 ± 60	[14, 15]
24	The same	The same	4.00	2.5	440 ± 50	[14, 15]
25	Corundum 5	The same	2.00	1.0	450 ± 50	[14, 15]
26	The same	The same	3.00	1.0	470 ± 40	[14, 15]
27	The same	The same	4.00	1.0	500 ± 40	[14, 15]
28	Corundum 6	The same	2.00	1.0	470 ± 50	[14, 15]
29	The same	The same	3.00	1.0	500 ± 40	[14, 15]
30	The same	The same	4.00	1.0	550 ± 40	[14, 15]
31	Corundum 7	The same	2.00	1.0	302 ± 40	[14, 15]
32	The same	The same	3.00	1.0	315 ± 40	[14, 15]
33	The same	The same	4.00	1.0	330 ± 40	[14, 15]



**Fig. 1** The effect of the particle size on the strength of the interparticle contact (a) and the interparticle layer thickness (b). Numbers along curves I and II are the sequence numbers of the materials in Table 1 and 2, respectively.

creases as the particle size increases. The correlation coefficient is about 0.80.

The dependences of the interparticle contact strength on the particle size for all materials are approximated in logarithmic coordinates by straight lines (Fig. 1a). The correlation coefficient for compact materials is 0.92, and for porous materials it is over 0.85. In this case the experimental points

for compact materials fall in the same straight line regardless of the type and quantity of the additives.

The tangent of this straight line angle for porous materials is close to 1.10. The strength of the interparticle contact increases with increase in the amount of the additive. The highly disperse zirconium dioxide (additive 1) gives greater values of  $P$ , the weights being equal, than additive 2 of the eutectic composition. The difference in the position of the straight lines for materials with different additives points to the sensitivity of the parameter  $P$  to the material composition, while the integral strength is weakly related to this factor. It can be assumed that the fracture of porous materials occurs in the areas of interparticle contacts, and the greater the size of these areas determined by the amount of additive and the size of the corundum particles, the more easily the material breaks. The decrease in the integral strength of the material with increasing corundum particle size and increasing strength of the interparticle contact is related to a more intense (in proportion to the cube of dimension) decrease in the number of contacts per material volume unit, compared to the linear increase in  $P$ .

For dense materials, the function  $\ln P(\ln d)$  is described by a straight line with the tangent of the slope equal to 2.03, which is close to the theoretical dependence  $P \sim d^2$ .

Thus, the dependence of the single contact strength on the particle size is preserved not only in porous but in dense materials as well. The difference in the exponent of the size of particle  $d$  for materials of different structures is probably related to the specifics of stress distribution.

In addition, the effect of the thickness of the interparticle interlayer on the strength of the contacts was assessed. The latter was calculated as the difference between the "fictitious" and the actual radius of the particle in the absence of intense interaction between the high-melting phase and the

**TABLE 2**

No.	Particle size, $\mu\text{m}$	Additive	Additive weight content, %	Open porosity, %	Breaking strength, MPa
1	40	1	5	44.3	1.0
2	40	1	10	45.3	1.7
3	40	1	15	42.1	2.9
4	40	2	5	45.6	0.7
5	40	2	10	47.0	1.2
6	40	2	15	46.2	1.8
7	20	1	5	45.4	1.5
8	20	1	10	45.4	3.0
9	20	1	15	42.1	7.7
10	20	2	5	47.1	1.5
11	20	2	10	46.5	2.1
12	14	1	5	44.2	2.1
13	14	1	10	47.2	3.6
14	14	1	15	43.0	8.2
15	14	2	5	45.6	2.0
16	14	2	10	44.2	2.5
17	7	1	5	42.2	7.3
18	7	1	10	40.4	11.0
19	7	1	15	40.8	10.7
20	7	2	10	43.9	7.0

sintering additive, its constant molar volume, and uniform distribution over the surface of the corundum particles.

The dependence of the thickness of the interparticle layer on the corundum particle size (Fig. 1b) in logarithmic coordinates is linear as well both for porous and dense materials. The exponent of the particle size  $d$  in this case is close to 1. This confirms the known assumption that the fracture of the corundum material proceeds according to the same mechanism, regardless of its structure and the type and quantity of additives. It should be noted that the assessment of the interparticle contact thickness in porous materials is probably somewhat underestimated due to the coalescence of the second phase in the interparticle contact meniscus.

A correlation between  $P$  and  $h^2$  is observed for dense materials, whereas the value  $P$  for porous materials is linearly related to  $h$ . The latter is determined by the nature of distribution of the additive over the corundum particles surface. An increase in the particle size produces a linear decrease in the specific surface area and an increase in the interparticle layer thickness in dense materials. The additive in porous materials is concentrated in the areas of interparticle contacts, and its amount depends on the number of these contacts.

Thus, the use of the parameter of interparticle contact strength and interparticle layer thickness in the analysis makes it possible to clarify the specifics of ceramic material fracture and ways for improving their qualities.

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